Today's Technology PROTECTING Tomorrow's Groundwater

CONFERENCE PROCEEDINGS

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Geophysical Applications to Groundwater Resources

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ABSTRACT

Water is a valuable resource and a necessary staple to sustain life. Although water covers more than 75 percent of the earth's surface, potable water is not always easily accessible. Random drilling is frequently used to locate this resource, often with disappointing results. Technological advancements with geophysical instrumentation have dramatically decreased the randomness of well placement for locating significant sources of potable water.

Two types of geophysical surveys can assist in finding water, resistivity and VLF. A resistivity survey uses an earth resistivity meter to measure the resistance of the soil and bedrock. Geophysicists can now create a 3-dimensional structure of a groundwater reservoir from resistivity data. A VLF survey uses very low frequency electromagnetic energy to find water-bearing fractures in bedrock. Three-dimensional VLF surveys can locate large fractures for placement of production wells. VLF surveys can also be used to determine the quality of water within a fracture.

Case studies have shown that geophysical field surveys eliminate the guesswork in finding groundwater and help bring this valuable resource to within our reach.

INTRODUCTION

Geophysical surveys provide a quick and inexpensive method for the evaluation of various subsurface phenomena related to the study of aquifers. Two geophysical methods described within this paper, resistivity and very low frequency (VLF) measurement have the potential to define the limit and properties of an aquifer. Resistivity measurements can help define the architecture of the reservoir, whereas, VLF surveys can locate fractures, a potential source of water, since fractures tend to improve the permeability of bedrock.

Electrical Resistivity Theory

Resistivity is one of the oldest geophysical methods and has been deployed for aquifer studies for nearly 100 years (Reynolds, 1997). Electrical resistance is based upon Ohm's Law:

$$R = \frac{V}{I}$$

Where, resistance, **R**, is equal to the difference between the current flow, **I**, and voltage differential, **V,** and depends upon the bulk property and geometry of the material, thus, resistivity is measured in Ohm-meters.

Currents are carried through earth materials by motion of the ions in connate water. Ions in connate water come from the dissociation of salts and provide for the flow of electric current. Further, resistivity decreases in water-bearing rocks and earth materials with increasing: a) Fractional volume of the rock occupied by water; b) Salinity content of the water; c) Permeability of the pore spaces; and d) Temperature. Materials that lack pore space (i.e., limestone, igneous rocks) or lack water in the pore space will show high resistivity (Mooney, 1958). Most earthen materials, however, show medium to low resistivity and can be imaged through resistivity measurements.

In homogeneous ground, the apparent resistivity is the true ground resistivity; however, in heterogeneous ground, the apparent resistivity represents a weighted average of all formations through which the current passes. Many electrode arrays have been proposed (for examples see Reynolds, 1997); however, the dipole-dipole array has proven to be the most effective configuration for imaging shallow channels in bedrock settings. The following dipole-dipole configuration was used in the collection of data:

$$R_i = \pi n(n+1)(n+2)a\frac{V}{I}$$

Where, $\mathbf{R_i}$, resistivity, is related to the number of poles, n, and pole spacing, **a**, is from Ohm's Law.

Maximum imaging of the channel is based upon dipole-dipole spacing and pole spacing is derived from:

$$D = \frac{BA}{2} + \frac{AM}{2}$$

Where, the depth, **D**, is a function of the pole spacing for the electrodes, **A**, **B**, and **M**. The pole spacing for the collection of data is dependent upon the depth of interest and detail.

Electromagnetic (VLF) Theory

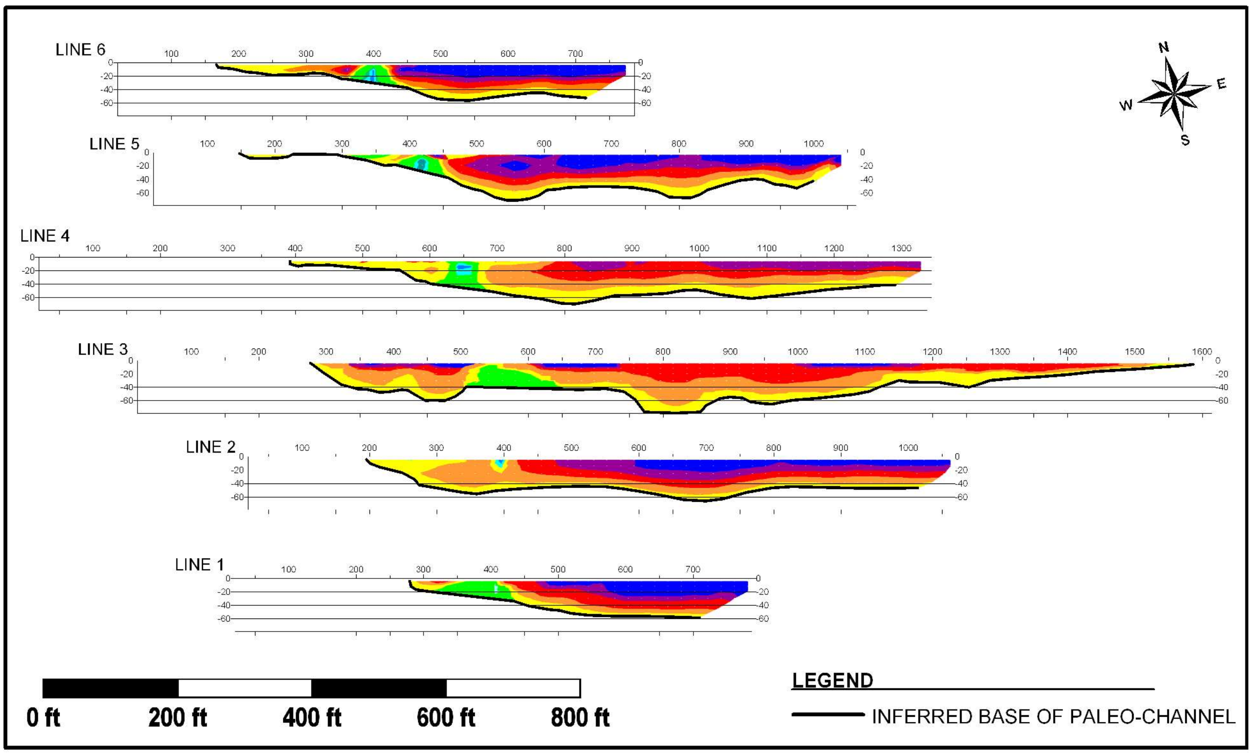
VLF is a military radio signal having an electromagnetic frequency of 15 - 30 kHz that is used for communications, but also travels through the shallow subsurface. VLF methods for fracture identification have been around for at least 50 years when the first commercial ground unit was developed in 1964 (Paterson and Ronka 1971). The VLF method can be used to find steeply dipping structures that differ form their surroundings with regard to electrical resistance. When the field emitted by a transmitter strikes a vertical anomaly, secondary currents are created that can be read and recorded by a VLF instrument. Anomalies can be caused by more than just fractures. For example, cables, metal pipes, and electrical fences are grounded, which permits a large ground-return current loop to form, showing a similar signature to that of fractured bedrock (ABEM Geophysics, 1989).

METHODS

Case 1 - Resistivity

The General Authority of the City of Franklin is installing a well field in an abandoned Pleistocene channel that is adjacent to French Creek. The City planned to install production wells for providing sufficient water for the community; however, the number of well installations was limited due to cost. Six dipole-dipole resistivity surveys were collected to determine the maximum depth of the reservoir and the best location for well placement (Figure 1). The east-west lines (800 to 1,650 feet long) were oriented normal to the interpreted thalweg of the abandoned channel.

Figure 1 Resistivity profiles oriented normal to the trend of the Pleistocene-aged paleo-channel in Franklin, Pennsylvania showing profiles of the channel from north to south. Depth scale is in feet below base grade.



Case 1 study consisted of defining the horizontal and vertical extent of the paleo-channel for placement of production wells using resistivity. The unconsolidated channel sediments are estimated to have resistivity values of less than 40 Ohm-meters; whereas, bedrock (i.e., Paleozoic shale and sandstone) is estimated at greater than 40 Ohm-meters.

The resistivity survey was performed using the Sting R1 IP coupled with the Swift controller (Advanced Geosciences, Inc., Austin TX). Long lines dictate the use of roll-along survey techniques, whereby data is continuously collected as the cables are repositioned. The survey was conducted using a 200-volt DC source, stainless-steel poles, and Swift cables.

A forward modeling subroutine was used to calculate the apparent resistivity values using the RES2DINV program (Loke, 1998). This program is based upon the smoothness-constrained least-squares method (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996).

Case 2 - VLF

Case 2 study consisted of locating drilling sites in Triassic-aged consolidated bedrock for the production of groundwater for a proposed subdivision in Wake Forest County, North Carolina. Fractures provide permeability and storage for groundwater production in impermeable bedrock and were identified through a VLF survey using the Wadi (ABEM AB, Bromma, Sweden). The 23.9-MHz signal from the transmitter located in Cutler, Maine was used as the source.

VLF data were collected every ten meters along four traverses between two east-west oriented ridges. The ridges axes were determined by aerial photographic methods to be cut normally by regional fractures. Frasier filtering is a numeric algorithm that was performed on the real part of the VLF data to enhance the anomaly indication. Fraser filtering is based upon the work of Karous and Hjelt (1983):

$$F_0 = K(0.102\,H_{-3} + 0.059\,H_{-2} 0.561\,H_{-1} + 0.561\,H_1 - 0.059\,H_2 + 0.102\,H_3)$$

Where; F_0 is the filtered result and H_{-3} to H_3 is the original VLF data and K is the constant that represents the distance between readings.

INTERPRETATION

Case 1 - Resistivity

The cross-section of the paleo-channel is well displayed by the resistivity profiles (Figure 1). The channel is shallow (less than 60 feet deep), 1,400 feet wide and oriented north-south. An isopach map of the channel thickness shows that the thickest portion of the channel occurs in the central portion of the survey area (Figure 2). There is an anomalous thinning of the channel as depicted on Line 3 that was verified with the installation of a well. Additional well installations have shown that the thickest portion of the channel is located as shown on the isopach map (Figure 2). Finally, pump tests in wells installed through the thickest portion of the channel have proven that the channel has a high yield (up to 350 gallons/minute).

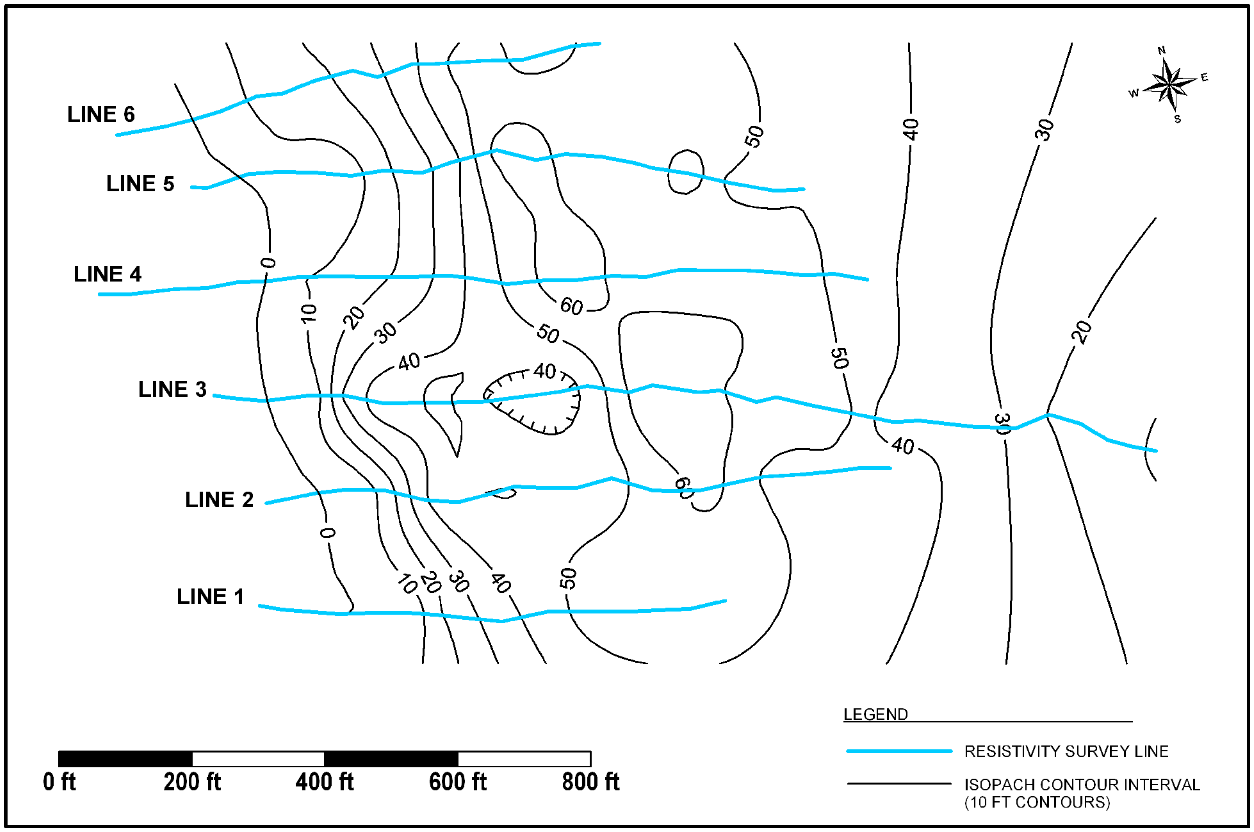


Figure 2 **Isopach map of the paleo-channel thickness as defined by resistivity profiling.**

Case 2 - VLF

A VLF survey performed in an undeveloped portion of Wake County, North Carolina located fracture sets that, when drilled, produced significant volumes of water (Figure 3). Fractures were ranked and divided into four fracture zones based upon a decision matrix that included a systematic ranking for the following parameters: Fraser-filtered VLF magnitude; imaginary VLF magnitude; lateral continuity; proximity to other fractures; surface expression; and, aerial photographic expression. The imaginary data is a measurement of the conductivity of the groundwater, a useful component of groundwater prospecting. Further, research has shown that long fractures are more readily associated with better groundwater production (Kulander, et al., 1980); consequently, long fractures were ranked higher than short fractures. The grouping of fractures is an excellent indicator of broken bedrock and may indicate good groundwater production.

Fractures were divided into 4 fracture zones based upon the occurrence of similar physical features; Fracture Zone A has fewer fractures and higher conductivity, Fracture Zones B and C have more fractures and lower conductive fluids, and Fracture Zone D had more fractures with highly conductive fluids (Figure 3). Production wells installed in Fracture Zones B and C produced over 100 gallons per minute of potable water (i.e., conductivity less than 100 milliSiemens/meter).

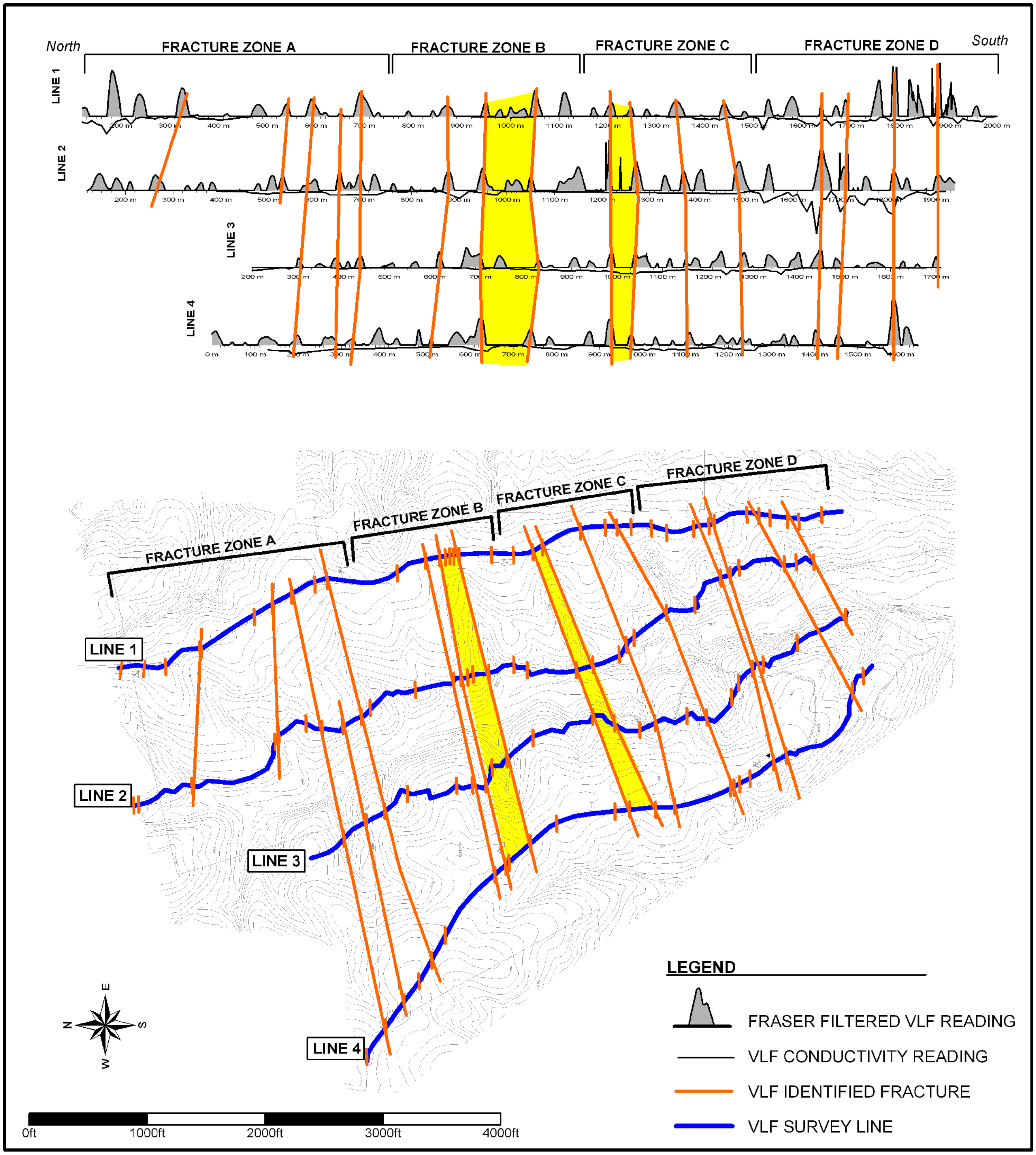


Figure 3 **Fraser-filtered VLF survey lines showing fractures (above x-axis) and fluid conductivity (below x-axis) and interpretation of the fracture pattern on the topographic map.**

CONCLUSION

A paleo-channel was imaged through dipole-dipole resistivity profile mapping. The channel shows downcutting and infilling into the Paleozoic sediments to about 60 feet. The channel fill has an apparent resistivity of 40 Ohm-meters or less. The resistivity survey results agree well with the interpretation provided by borings installed at the site. The thickest sediment is located in the central part of the study area and sediment in this area proved to provide excellent production (up to 350 gallons per minute).

VLF analysis of a proposed subdivision in Wake Forest, North Carolina showed two prominent fracture sets. Bedrock fracturing is associated with groundwater production and these fracture sets, when drilled, produced commercial quantities of groundwater (greater than 100 gallons per minute). Further, the interpreted low specific conductivity of the groundwater associated with these two fracture sets was substantiated through well testing.

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